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EFFECTS OF SEVERAL ALLOY PRODUCTION AND FABRICATION VARIABLES ON THE SHARP NOTCH PROPERTIES OF 5Al-2.5Sn-Ti SHEET AT LIQUID HYDROGEN TEMPERATURE

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INTRODUCTION

At liquid hydrogen temperature the strongest weldable aluminum alloys have yield strength to density ratios less than 900,000 (1) (2). If higher strength to density ratios are desired either titanium alloys or cold rolled metastable stainless steels must be employed.

Metastable stainless steels cold rolled sufficiently to give $-423^{\circ}F$ yield strength to density values above 1,000,000 possess a number of characteristics which make them marginal materials for use in liquid hydrogen tankage. Thus, as previously shown (3) (4) AISI 301 exhibits a substantial decrease in crack tolerance as the temperature is reduced from -320 to $-423^{\circ}F$. Both AISI 301 and 304 steels show high directionality of fracture toughness due to heavy cold rolling with the transverse toughness being relatively poor over the temperature range from +75 to $-423^{\circ}F$ (5). Furthermore, welds in metastable stainless steels are transformed to essentially 100 per cent martensite by very small plastic strains at $-423^{\circ}F$ and such transformed regions can act as crack starters.

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Titanium alloys, like the stainless steels, exhibit a decrease in crack tolerance as the test temperature is reduced from -320 to -423^{O}F. However, if the impurity content is sufficiently low the annealed α alloy, 5Al-2.5Sn-Ti, has a better resistance to crack propagation at -423^{O}F than AISI 301 at the same yield strength level (3). Additional advantages result from the use of this alloy in the annealed condition; namely, there is essentially no directionality of the sharp notch properties, and welds have approximately the same strength as the parent metal and are stable at low temperatures. However, very little is known regarding the influence of various alloy production and fabrication variables on the fracture toughness of 5Al-2.5Sn-Ti sheet and such knowledge is necessary in order to permit rational hardware design.

The object of the present investigation was to determine the influence of the following alloy production and fabrication variables on the smooth and sharp notch strength of 5Al-2.5Sn-Ti sheet: (1) sheet thickness; (2) small amounts of cold rolling such as might be applied in flattening; (3) stretching in uniaxial tension; (4) cooling rate from the annealing temperature; and (5) fusion welding. Investigations of sheet thickness involved tests over a range of low temperatures on material at three interstitial levels. The majority of the remaining variables were studied at -423^{O}F using a low interstitial composition typical of that which might be specified for liquid hydrogen service.

MATERIAL

Four heats of 5Al-2.5Sn-Ti were investigated having the compositions shown in Table I. The heats designated as normal interstitial had impurity contents typical of commercial grade alloy. The remaining two heats were produced by using a low hardness sponge with no scrap additions. These are designated as low interstitial I and low interstitial II. The first was an experimental heat and the second a commercial heat produced to General Dynamics/Astronautics specification No. ES 0-71010. This specification was designed to limit the interstitial and iron content to the lowest values consistent with reasonable production costs. Both of the low interstitial heats had closely matching impurity contents with the exception of nitrogen and hydrogen, which were significantly higher in the commercial heat (low interstitial II).

As indicated in Table I all sheet was given a $1500^{\circ}F$ anneal in either vacuum or argon and furnace cooled. Material annealed in the authors' laboratory had previously received lower temperature annealing at the mill which in some cases did not entirely remove all evidences of cold work. It is to be noted that after the annealing treatments of Table I, the microstructure showed no evidence of cold work. A typical example is given in Figure 1 which shows equiaxed grains characteristic of annealing below the β transus.

PROCEDURE

The material conditions and variables investigated are outlined in Table II. Details of the rolling, stretching and welding procedures are given in the Appendix. Sharp edge notch tests were used to establish the influence of the various material conditions on the fracture characteristics at cryogenic temperature. The following section presents details concerning specimen preparation and testing procedure as well as the method of presenting the data.

Specimen Preparation and Testing

The smooth and sharp edge notch tension specimens are shown in Figure 2. Details regarding the design and preparation of sharp-edge notch tension specimens for screening purposes are described in a report of the ASTM Committee on the Fracture Testing of High Strength Sheet Materials (6). The notch specimen employed in this investigation is basically that described by the ASTM Committee, except that notch radii were held to 0.0005 inch maximum instead of the 0.001 inch mentioned in the Committee report. With the exception of the welded samples, machining for both smooth and notch specimens was confined to the sheet edges, since pressure vessels are not normally subject to surface machining. Weld samples had their weld bead machined flush with the adjacent sheet. This does not coincide with commercial practice in the fabrication of component hardware but was necessary to determine the properties of the weldment itself.

Details of the room temperature testing procedure follow ASTM recommendations (6). Tests at low temperature employed essentially the same techniques except that the specimen was surrounded by an insulated can containing a cold fluid. For tests at $-423^{o}F$ liquid hydrogen was used, at $-320^{o}F$ liquid nitrogen, and at $-110^{o}F$ a mixture of dry ice and ethyl alcohol.

Data Presentation

While Table II gives all conditions investigated, not all of the corresponding data is reported in this paper but, rather, an attempt has been made to illustrate typical behaviors.

In representing sharp notch data both the conventional notch strength and the nominal fracture toughness (K_{cn}) are shown. The K_{cn} values were calculated by methods outlined previously (6) with the exception that the crack length at unstable fracture has been assumed equal to the original total notch length (e.g., 2a = 0.30 inch). The resulting nominal fracture toughness is a minimum value that is always less than the true value if slow crack extension occurs. As pointed out by Srawley (7) the use of nominal values has some merit since they lead to a more conservative evaluation of the alloy than do the true values. This conservatism is desirable because there is no known way of predicting the slow growth of a crack in a component when operating loads are applied. The per cent shear has also been reported in a few cases. This was determined from measurements made at or near the longitudinal centerline of the specimen.

INFLUENCE OF TEST TEMPERATURE AND SHEET THICKNESS

The behavior of titanium alloys at low temperatures has been summarized by Holden et al (8) who point out that low temperature brittleness is increased by a high content of the interstitial elements carbon, oxygen, nitrogen and hydrogen. For this reason most specifications limit the interstitial element content of titanium alloys to values presumably low enough to avoid significant embrittlement. However, in a previous NASA investigation (3) it was shown that the -423^{o}F fracture toughness of 5Al-2.5Sn-Ti sheet could be significantly improved by further reducing the content of interstitial elements below that normally specified for commercial grade alloy. The corresponding loss in smooth tensile strength was relatively small and -423^{o}F yield strength to density ratios well above 1,200,000 were achieved. Several other investigators, notably Schwartzberg and Keys (9) and Christian et al (10) have recently published sheet tensile data showing the influence of interstitials on the cryogenic notch properties. These investigations were made using mildly notched specimens and the results are therefore not directly comparable with those obtained in previous NASA investigations. However, the mild notch data does show a definite increase in notch sensitivity as the interstitial content is raised. Christian also presents a limited amount of data on the influence of iron which indicates this element may also have an embrittling effect.

No data exists concerning the effects of thickness on the fracture characteristics of titanium alloys at low temperature. However, a thickness effect might be expected from the behavior of high strength alloys tested at room temperature (11) (12). Thus, the range of very low thicknesses are characterized by full shear fractures and increasing fracture toughness with increasing thickness. This behavior is apparently related to the fact that the crack tip plastic zone for a full shear fracture tends to extend an amount proportional to the sheet thickness. As the thickness further increases the fracture toughness passes through a maximum and decreases rather rapidly in a narrow range of thickness and eventually reaches the value characteristic of plane strain fracture. This transition behavior in terms of thickness has been described in detail elsewhere (11) (12) and is associated with rapidly developing lateral constraint as the thickness begins to exceed about twice the crack tip plastic zone radius.

The following section will present results illustrating how the effect of test temperature on the smooth and sharp notch properties is modified by the interstitial level. In addition, the effects of thickness on the fracture properties at three interstitial levels will be shown for tests at $-423^{o}F$.

Effect of Test Temperature

Typical examples of the influence of test temperature on the smooth and sharp-edge notch strength of a low and normal interstitial alloy are shown in Figures 3a and 3b respectively for 1/16 inch thick sheet. The smooth strength values at both interstitial levels exhibit the pronounced temperature dependence characteristic of titanium alloys. As might be expected, the smooth tensile and yield strengths of the normal interstitial material are somewhat higher than those for the low interstitial alloy. This difference, however, is less than 10 per cent over the temperature range investigated. For both alloys no practical significant difference was observed in smooth strength values between longitudinal and transverse tests.

In contrast to the behavior of smooth specimens, the sharp notch strength trend with test temperature is different for the two interstitial levels. Thus, a rapid decrease (transition) in notch strength with decreasing temperature is observed for the low interstitial alloy below -320^{o}F, while this transition occurs at a much higher temperature (approximately -150^{o}F) for the normal interstitial sheet. Within the range of thickness investigated the notch strength transition temperature increases with increasing thickness for the normal interstitial alloy but appears to be essentially independent of thickness for the low interstitial material.

Influence of Sheet Thickness

The influence of sheet thickness on the fracture characteristics at -423^{o}F is shown in Fig. 4 for material at three interstitial levels. Smooth strength values for a given composition were essentially independent of thickness. The yield strength levels for Low Interstitial I, Low Interstitial II and Normal Interstitial sheet were 202,000, 212,000 and 230,000 psi respectively.

The general effect of thickness conforms to that previously observed in room temperature tests in that the notch to yield strength ratio and the nominal fracture toughness first increase with an increase in thickness to a maximum value and then exhibit a decrease in a rather narrow thickness range. A corresponding transition in fracture appearance (per cent shear) with increasing thickness occurs and this is more pronounced than that observed in fracture toughness.

It will be noted that the magnitude of the thickness effect is considerably influenced by the interstitial element content. It would appear that the transition thickness is shifted downward with an increase in interstitials. Furthermore, at thicknesses above the transition range all three fracture parameters shown in Fig. 4 are lowered with increasing interstitial element content. Particular attention should be given to the fracture appearance curve for normal interstitial sheet which shows a rapidly developing embrittlement between 0.050 and 0.125 inch thickness. In fact, the 0.125 inch sheet exhibits a nearly flat fracture and it might be expected that crack propagation in sheet of this thickness and greater would be controlled by the plane strain toughness.

INFLUENCE OF STRETCHING AND ROLLING

Titanium sheet alloys are commonly subjected to stretching in various fabrication procedures. However, with the exception of flattening passes sometimes given after final annealing, cold rolling of titanium alloys is not a normal practice.

There is considerable data (14) showing the influence of moderate stretching (up to 5 per cent) on the room temperature tensile properties of titanium alloy sheet. For α alloys and annealed $\alpha + \beta$ alloys the tensile yield strength is increased only a small amount by the first few per cent stretching and then does not change with further stretching. Geil and Carwile (15) report that room temperature prestretching (up to 12 per cent) of bar stock did not affect the $-320^{o}F$ smooth or mild notch strength of pure titanium but markedly reduced the $-320^{o}F$ notch strength of 4Al-4Mn-Ti without a corresponding increase in smooth strength. In a study of 0.41N-Titanium, Ripling (16) found an improvement in room temperature ductility of sharply notched bars with prestrains up to 6 per cent but an embrittling effect at higher prestrains. Recently Christian et al (10) reported that strengthening with no accompanying mild notch embrittlement at $-423^{o}F$ is associated with double radius stretch forming of 5Al-2.5Sn-Ti sheet. However, no experimental details [redacted] are provided.

Petunina and Poplavskaya (13) investigated the influence of cold rolling up to 30 per cent on the room temperature tensile and bend properties of a 3Al-2V-Ti sheet alloy. Reductions up to about 20 per cent produced significant increases (approx. 20 per cent) in tensile yield strength, but rapid loss in elongation, reduction of area and bend angle. The data for 30 per cent reduction indicate a decrease in the rate of change of these properties for rolling beyond about 20 per cent.

Christian et al (10) report similar behavior for 5Al-2.5Sn-Ti sheet rolled up to 50 per cent. Reductions up to 10 per cent produce an increase in strength of about 20 per cent at room temperature and 10 per cent at $-423^{o}F$. Heavier rolling produced no further significant strength increase at either temperature. Mild notch data indicated that two heats exhibited brittleness at $-423^{o}F$ for reductions in excess of 10 per cent. A third heat with lower interstitial content showed no embrittlement for reductions up to 20 per cent.

From the above review of published results it would be expected that moderate amounts of stretching or rolling would not produce large strength increases in α titanium alloys at cryogenic temperatures and that the effect of these variables on the fracture properties would depend in large part on the composition. The present study was designed to explore the influence of stretching up to a value higher than normally encountered during fabrication and to determine the effects of small reductions by rolling on the $-423^{o}F$ smooth and sharp notch properties of low interstitial sheet.

Results for Stretching

The results for three initial thicknesses of low interstitial sheet tested at $-423^{o}F$ are given in Fig. 5 as a function of per cent stretching. It is important to note that the solid and open points do not refer to longitudinal and transverse in the sense used in other figures but refer to the direction of stretching with respect to the original sheet rolling direction. All specimens were tested in the stretching direction (see Appendix). The smooth strength, Fig. 5a, is shown only for 0.025 inch thick sheet, since the other thicknesses investigated exhibited essentially identical trends. The tensile and yield strengths are increased about 10 per cent by stretching 12 per cent. Additional stretching would not appear to produce a further increase in strength.

The influence of stretching on the notch strength, Fig. 5a, and fracture toughness, Fig. 5b, depends on the initial thickness. Thus, the 0.060 inch thick sheet[1] is unaffected by stretching while both the 0.025 and 0.010 inch thick sheet exhibit a definite improvement in fracture properties in the range of small stretching strains. The authors have no explanation for this effect since, as will be mentioned later, no improvement in nominal fracture toughness is noted due to prestraining equivalent amounts by cold rolling.

Results for Rolling

The results for 0.025 inch low interstitial sheet tested at $-423^{\circ}F$ are shown in Fig. 6 as a function of reduction by rolling. Essentially identical behavior was observed for 0.010 inch thick sheet. The tensile and yield strengths increase with per cent reduction and reach a constant value between 6 and 10 per cent reduction. The elevation in tensile strength is approximately 10 per cent while the yield strength increases 7 per cent. The notch strength and fracture toughness are unaffected over the range of rolling reductions investigated.

ANNEALING TREATMENT

The occurance of ordering reactions in the titanium-aluminum system is well known. Maykuth et al (17) have summarized a number of investigations of the Ti-Al binary diagram and show the presence of an ordered α_2 (assumed to be Ti_3Al) phase field in the range of low aluminum content. The lower composition boundry of this phase at $1022^{\circ}F$ is fixed by the data of Crossley and Carew (18) at 6 weight per cent aluminum or lower.[2] It might be expected that the presence of an ordered α_2 phase could adversely affect the fracture

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1. This thickness sheet was mill line annealed at $1400^{\circ}F$ and air cooled. The .025 and .010 inch sheet were reannealed at the NASA according to Table I.

2. A recent study by Clark et al (20) has modified this diagram for compositions greater than 7.8 weight per cent aluminum at temperatures of $1200^{\circ}F$ and above. However, these modifications do not help establish the α_2 boundry at temperatures below $1000^{\circ}F$.

properties of titanium alloys. Thus, data developed by Titanium Metals Corporation of America (19) show the fracture toughness of milled annealed (furnace cooled) 8Al-1Mo-1V-Ti sheet to be increased about 75 per cent by a very short reanneal followed by air cooling. This increase in fracture toughness is likely due to the absence of the ordered phase in the air cooled material.

This portion of the present investigation was designed to determine whether or not the cooling rate from the annealing temperature would affect the cryogenic fracture properties of 5Al-2.5Sn-Ti alloy sheet. Specimens of various thicknesses of Low Interstitial II sheet were "air cooled" from the annealing temperature. This was accomplished by removing the sealed argon-filled specimen container from the furnace and allowing it to cool in still air. The fracture properties of air cooled specimens are compared in Fig. 8 with those of specimens given the usual furnace cool. This latter cooling rate corresponds to that which might be encountered in a mill vacuum anneal. The smooth tensile properties were essentially identical for the two cooling rates. However, the sharp notch behavior was quite different in the range of thicker sheet. Thus, the nominal fracture toughness of sheet equal to or greater than 0.060 inch is increased about 50 per cent by air cooling.

WELDING

There is apparently no published information concerning the behavior of α-titanium weldments in the presence of sharp notches. In the present investigation, sharp notch properties were determined for welded 5Al-2.5Sn-Ti alloy sheet at two interstitial levels. Possible areas of embrittlement due to welding were first explored through careful metallographic examination of the fusion and heat affected zones and Vickers hardness surveys of a section through the weld and perpendicular to the sheet surface. Results typical for all sheet are illustrated in Figure 7 which shows the hardness distribution along several locations through the thickness as well as the microstructure of the welded sheet. The hardness survey indicates only random variations from the base metal to the weld centerline. Examination of the microstructure reveals very large acicular grains in the weld fusion zone as the only identifiable region of possible embrittlement. Thus, on the basis of these observations the notch was located at the weld centerline.

The smooth and sharp notch properties of welded specimens at room temperature and $-423^{\circ}F$ are shown in Table III for 0.025 normal and low interstitial sheet as well as the $-423^{\circ}F$ properties for 0.125 inch normal interstitial material. In addition, the corresponding properties of the base metal are given for the purpose of comparison. It should be noted that the designation longitudinal and transverse can properly be applied only to the base metal properties since the weld metal should be essentially non-directional.

According to Table III there is very little difference between the smooth and notch properties of weld metal and that of the parent plate. Thus, the higher smooth strength and lower toughness of the normal as compared with low interstitial sheet is reflected in welds made in these alloys.

PRACTICAL SIGNIFICANCE OF RESULTS

The previous sections have described the effect of certain material production and fabrication variables on the $-423^{\circ}F$ smooth and sharp notch properties of 5Al-2.5Sn-Ti sheet alloy. No claim is made to have defined or investigated all important variables in either category. However, on the basis of the results presented it is possible to make certain observations of practical interest to the producers and users of titanium alloys.

Alloy Production Variables

Alloy production variables included in this study were sheet thickness, interstitial level, cold rolling and annealing treatment.

The effects of sheet thickness and interstitial level on the fracture toughness are interrelated. Thus, the thickness range in which the toughness exhibits a transition (see Fig. 4) is shifted to thicker gages by a reduction in interstitial content. This behavior indicates that the need for low interstitial material becomes more critical as the section size increases. It is possible that additional toughness in thick sheet and in heavier sections can be gained by further reductions in the interstitial content below that designated as "low" by present commercial standards. This observation is based on the behavior of only two heats (compare Low I and Low II in Fig. 4) but recognizes the fact that interstitial elements in extremely small quantities can influence the fracture characteristics. The small loss in smooth tensile and yield strength at cryogenic temperatures caused by reductions in the interstitials are far outweighed by the increase in crack propagation resistance.

It is the authors' opinion that further progress in reducing the interstitial (or other impurity) embrittlement of titanium alloys cannot be made without systematically studying the individual effects of the various elements.* Such studies would permit

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* Odgen and Jaffee (21) proposed an oxygen equivalent effect for the influence of interstitials on the tensile properties of pure titanium, and Schwartzberg and Keys (9) have applied this to representations of notch data for 5Al-2.5Sn-Ti at cryogenic temperatures. Unfortunately the variations in interstitial levels for any one notch specimen type are not sufficient to establish the usefulness of this relation. It is also to be noted that Klier and Feola (22) attempted to establish the independent effects of the interstitials on 5Al-2.5Sn-Ti bar stock using sharply notched round bars. However, due to various experimental difficulties the data was not suited for the intended purpose.

definition of a reasonable goal in terms of desired properties and furnish some indication of the feasibility of achieving this goal in commercial production.

The cold rolling results are very encouraging in that small amounts of reduction (up to 10 per cent) produce a slight increase in smooth strength with no loss in nominal fracture toughness. Thus, it may be concluded that normal roll flattening operations after final annealing would have no deleterious effect. Other investigators have shown that substantial increases in room temperature strength are possible with higher reductions. However, there is no data available concerning associated changes in the fracture properties. It should be noted that in a previous publication (3) by one of the present authors, data was presented for 5Al-2.5Sn-Ti sheet rolled 19 per cent and tested at $-423^{\circ}F$. The sharp notch strength of this alloy was reduced below that of the annealed material and on this basis it was recommended that α titanium not be cold rolled. Re-examination of the cold rolled specimens and sheet stock indicated surface cracking, judged to be of sufficient magnitude to explain the deleterious effects of rolling. Surface cracking is difficult to avoid in cold rolling this alloy and particular care must be used to insure complete recrystallization during intermediate anneals.

The results of the annealing treatment study indicate that the ordered α_2 phase may exist in the 5Al-2.5Sn-Ti alloy at room temperature. Substantial increases in the nominal fracture toughness at $-423^{\circ}F$ apparently can be obtained by air cooling rather than furnace cooling from the annealing temperature.

Fabrication Variables

The two fabrication variables studied were uniaxial stretching and fusion welding without filler. Stretching (up to 16 per cent) increased the $-423^{\circ}F$ smooth strength slightly and had no detrimental effect on the nominal fracture toughness of low interstitial sheet. In fact, the toughness of thin gages appears to be improved by small amounts of stretching. The data obtained in this investigation related to tests in the stretching direction; however, the lack of directionality due to rolling would suggest that the stretched alloy is also non-directional. Results obtained by one other investigator at -320^{o}F on bar stock indicate that stretching may embrittle high interstitial α alloys. This is another argument for minimizing the interstitial level.

Tungsten inert gas fusion welds made without filler in either low or normal interstitial sheet had essentially the same smooth and sharp notch properties as the parent sheet at room temperature and -423^{o}F. The extremely large grain size and the presence of an acicular microstructure in the weld metal has apparently no adverse effect on its toughness.

APPENDIX: Procedures used in Stretching, Rolling and Welding

The following describes the procedures used for room temperature stretching, rolling and welding of annealed sheet.

Stretching

Stretching was performed at room temperature on the special pin-loaded stretch blanks shown in Figure 9 having their loading axis either longitudinal or transverse to the sheet rolling direction.

The longitudinal strain distribution in the smooth stretch blanks was determined from measurements of width and thickness over the gage section of the blank before and after stretching. The strain distribution was not completely uniform. However, it should be noted that the average strain over a central one-inch gage length was within 10 per cent of the maximum strain value.* The notch stretch blank was contoured so that the maximum strain occurred at the subsequent location of the notch.

After stretching, the blanks were machined to the contour of the specimens previously shown in Figure 2.

Rolling

Rolling was performed on individual specimen blanks at room temperature in a 4-high laboratory mill using 8-inch wide, 2 5/8 inch diameter carbide rolls with an 8 RMS surface finish. Rolling speed was approximately 50-75 feet per minute, and the rolling direction coincided with that of the as-received sheet. Care was taken to insure uniform reduction of the blank by liberal application of lubricant before each pass, by not exceeding 3 per cent reduction per pass, and by inverting the specimen blank between successive passes. This procedure produced flat stock without camber.

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* The maximum strain was forced to occur at the transverse centerline by slightly tapering the gage section of the smooth stretching blank.

Welding

All welding was performed by the General Dynamics/Astronautics Corporation using production welding techniques. Sheets were joined by TIG fusion welds utilizing argon gas shielding and no filler. Double pass welds (single pass each side) were made on the 0.125 inch gage material; only a single pass was required for the 0.025 inch sheet. Welds were made both parallel and perpendicular to the sheet rolling direction. Radiographs made of all welds revealed no porosity and photomicrographs showed overlap of all double pass weld beads. Specimen blanks were cut from the welded sheets with the loading axis perpendicular to the weld certerline. Weld beads were ground flush with the specimen surface.

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TABLE I. - COMPOSITION AND HEAT TREATMENT OF 5Al-2.5Sn-Ti SHEET ALLOYS

Interstitial content designation	Republic Steel Corp. heat no.	Composition, weight percent[a]							Thickness, in.	Annealing treatment
		Aluminum	Tin	Carbon	Nitrogen	Oxygen	Hydrogen, ppm	Iron		
Low I	XT 70025	4.88	2.45	0.029	0.004	0.103	8.0	0.120	0.015, 0.025, 0.063, 0.080	1500° F, 45 min (vacuum), furnace cool[b]
Low II	3960328	5.28	2.56	.028	.010	.100	40.0[d]	.110	0.010, 0.025, 0.060, 0.250	1500° F, 2 hr (argon), furnace cool[c]
Normal	3930031	5.28	2.59	.038	.009	.180	8.0	.160	0.015, 0.025, 0.063	1500° F, 45 min (vacuum), furnace cool[b]
Normal	3950620	5.20	2.48	.030	.014	.200	70.0	.170	0.125	1500° F, 2 hr (argon), furnace cool[c]

[a]Furnished by supplier unless otherwise noted.

[b]Annealed by alloy supplier.

[c]Reannealed by NASA.

[d]Determined by NASA.

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TABLE II. - MATERIAL CONDITIONS AND VARIABLES INVESTIGATED

Material condition[a]	Interstitial level	Sheet thickness, in.	Test temperature, °F
As annealed (see table I)	Low II	0.010, 0.025, 0.060, 0.250	R.T., -110, -320, -423
	Normal	0.015, 0.025, 0.063, 0.125	R.T., -110, -320, -423
Stretch 0 to 16 percent	Low I	0.025, 0.063	-423
Stretch 0 to 20 percent	Low II	0.010, 0.025, 0.063[b]	-423
Cold roll 0 to 10 percent	Low II	0.010, 0.025	-423
Tungsten inert gas fusion weld	Low I	0.025	R.T., -423
	Normal	0.025, 0.125	R.T., -423
Ann. 1500° F, 2 hr (argon), A. C.	Low II	0.010, 0.025, 0.060 0.250	-423

[a]All sheet initially in the annealed condition shown in table I, except as noted.

[b]Mill line annealed 1400° F, A. C.

TABLE III. - SMOOTH AND SHARP-EDGE NOTCH PROPERTIES OF BASE METAL AND WELDS IN LOW AND NORMAL INTERSTITIAL 5Al-2.5Sn-Ti SHEET ALLOY

	Base metal				Welded metal		
Direction	Tensile strength 10^3 psi	0.2 Percent yield strength 10^3 psi	Sharp-notch strength 10^3 psi	Fracture toughness $K_c n$ 10^3 psi $\sqrt{\text{in.}}$	Tensile strength 10^3 psi	Sharp-notch strength 10^3 psi	Fracture toughness $K_c n^*$ 10^3 psi $\sqrt{\text{in.}}$
0.025 Inch low I room temperature							
Long	100.0	97.0	119.0		96.0	109.0	
Long	97.8	94.7			93.3	107.0	
Trans	99.2	92.4	118.0			108.0	
Trans			117.0			108.0	
0.025 Inch low I -423° F							
Long	221.0	203.0	120.7	70.3	206.2	137.0	81.5
Long	222.0	202.5	141.0	83.1	204.2	107.0	60.7
Long	218.4	205.9	129.8	74.8		151.0	91.7
Trans	212.0	208.0	141.9	83.6		135.0	79.3
Trans	227.3	204.2	115.8	66.1			
Trans			119.6	68.0			
0.025 Inch normal room temperature							
Long	114.4	110.0	122.8		112.8	125.8	
Long	114.3	111.0	129.5		112.0	128.4	
Trans	117.5	112.8	127.0			128.7	
Trans			128.7				
0.025 Inch normal -423° F							
Long	235.0	207.0	119.0	67.1	234.0	117.2	66.1
Long	233.0	225.0	115.2	65.2	239.3	95.1	52.8
Long	238.0	230.5	110.3	57.2		111.3	62.6
Trans	229.0	226.0	111.0	62.4			
Trans	235.3	224.0	99.0	60.3			
Trans			128.3	73.4			

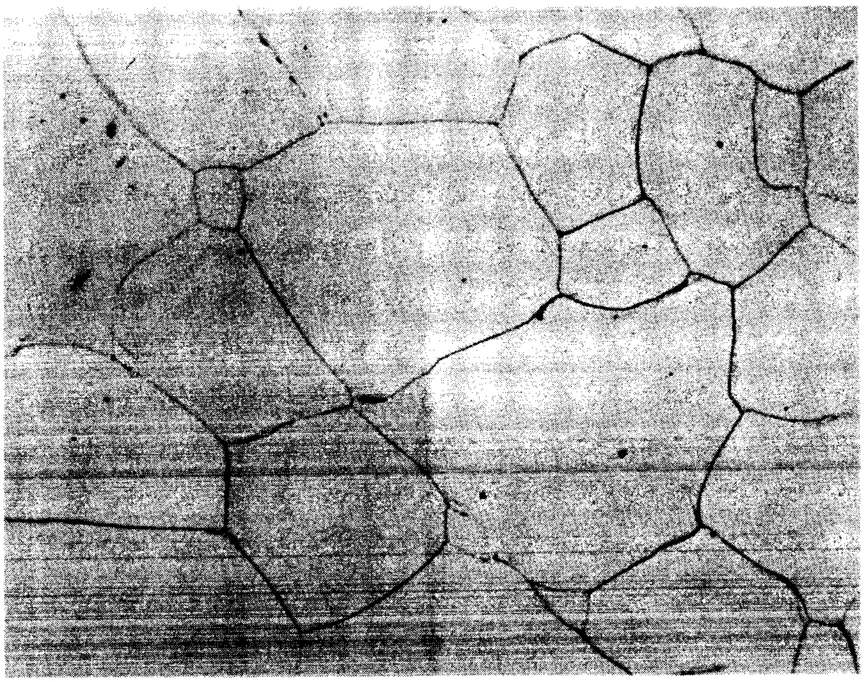
*For this calculation the yield strength of weld metal was taken as 95 percent of its tensile strength.

TABLE III. - Concluded. SMOOTH AND SHARP-EDGE NOTCH PROPERTIES OF BASE METAL AND WELDS IN LOW AND NORMAL INTERSTITIAL 5Al-2.5Sn-Ti SHEET ALLOY

	Base metal				Welded metal		
Direction	Tensile strength 10^3 psi	0.2 Percent yield strength 10^3 psi	Sharp-notch strength 10^3 psi	Fracture toughness K_cn 10^3 psi $\sqrt{in.}$	Tensile strength 10^3 psi	Sharp-notch strength 10^3 psi	Fracture toughness K_cn* 10^3 psi $\sqrt{in.}$
0.125 Inch normal -423° F							
Long	251.0	246.0	65.0	35.4	247.0	83.7	46.1
Long	252.0	246.0	71.3	38.9	246.0	99.5	55.3
Trans	232.0	232.0	63.4	34.5		89.3	49.3
Trans			66.5	36.2			

*For this calculation the yield strength of weld metal was taken as 95 percent of its tensile strength.

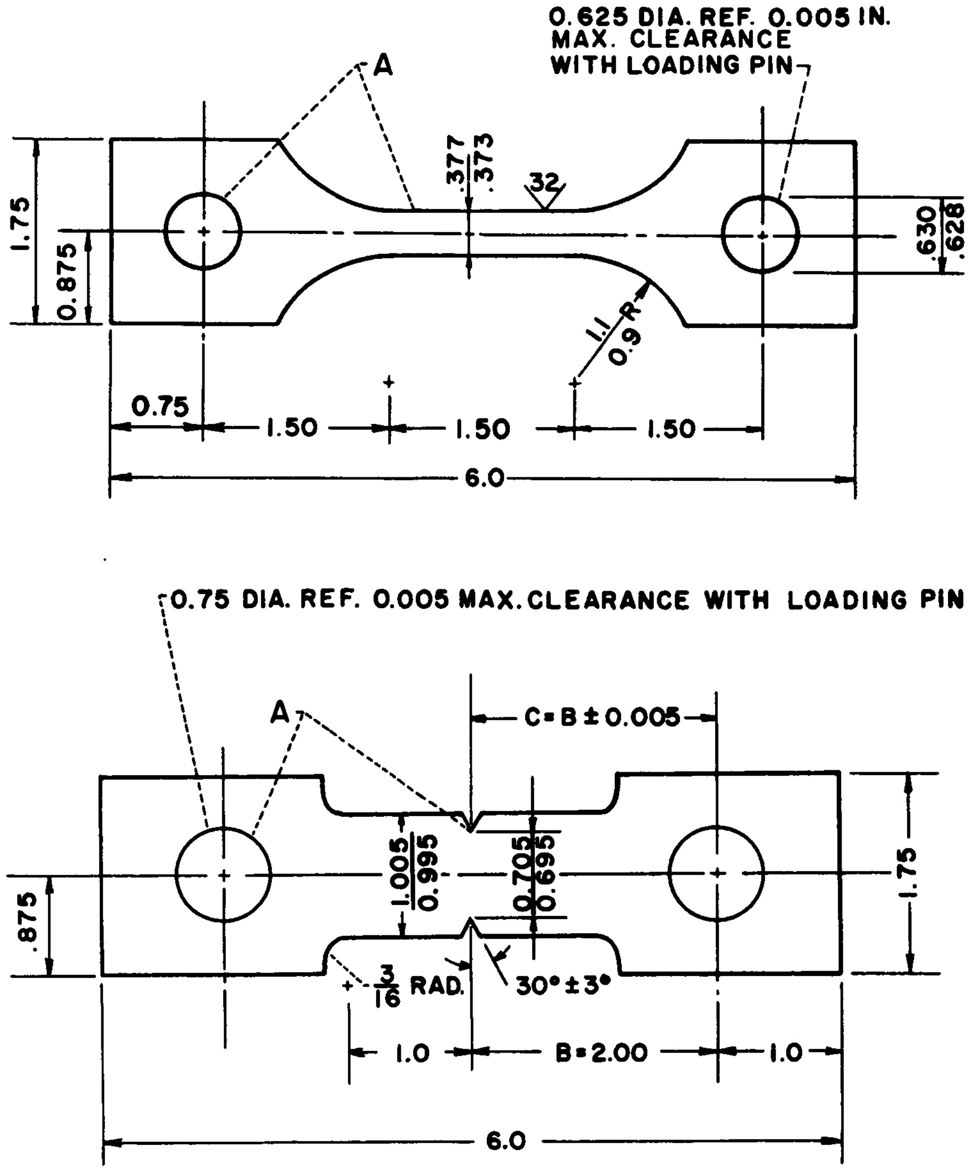
E-2163



C-64482

Figure 1. - Typical microstructure of 5 Al-2.5 Sn-Ti alloy annealed at 1500° F. X500. Etch: 30 lactic acid, 10 HNO_3, 5 HF.

E-2163



A SURFACES TRUE TO CENTERLINE WITHIN 0.001 IN.; NOTCH ROOT RADIUS 0.0007 IN. MAX.; UNLESS OTHERWISE NOTED, DIMENSIONS MAY VARY ± 0.01 IN.

Fig. 2. - Sharp edge notch and smooth tension specimens.

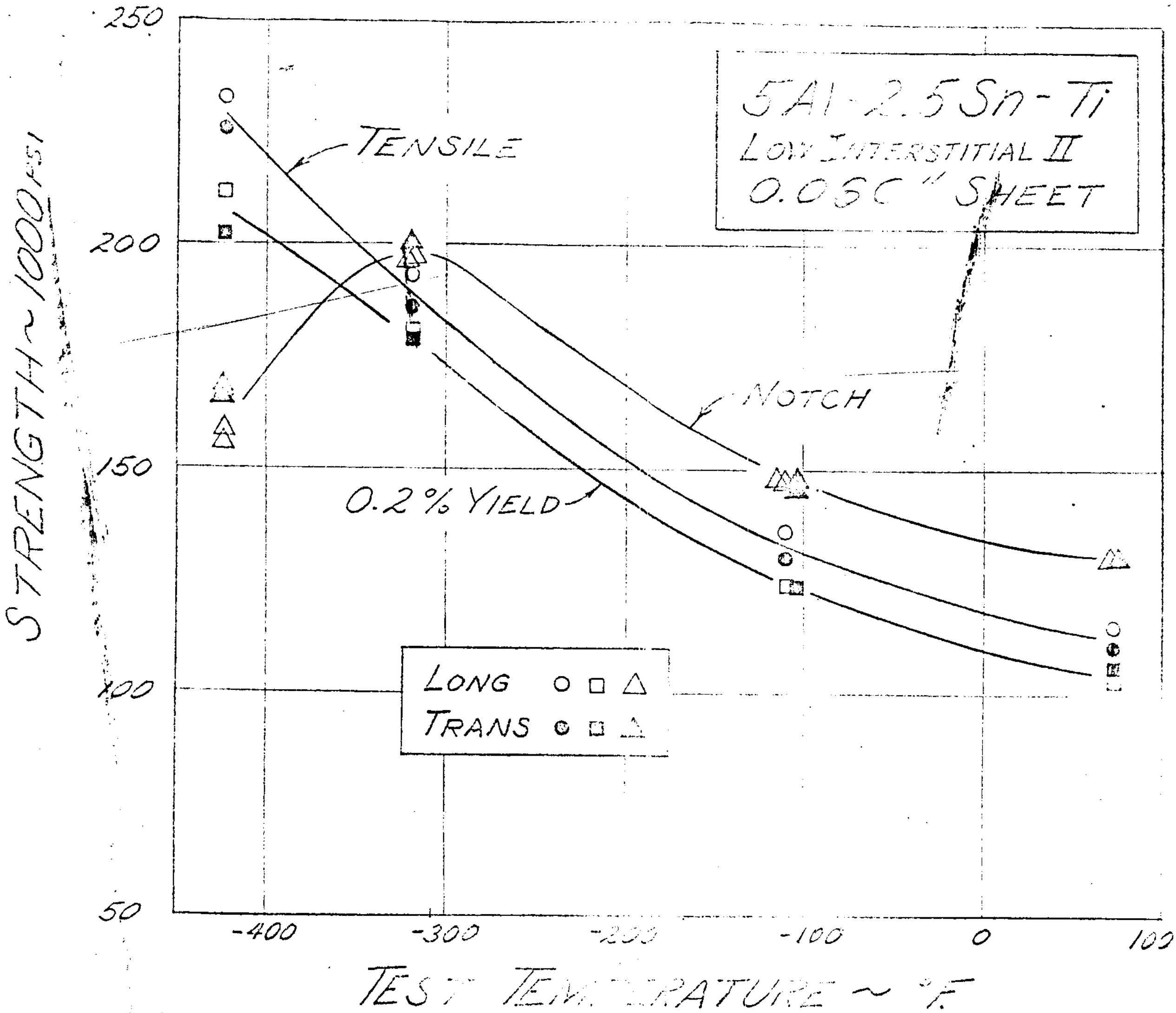


FIG. 3a: Influence of test temperature on smooth and sharp edge notch strength of low interstitial 5Al-2.5Sn-Ti alloy sheet.

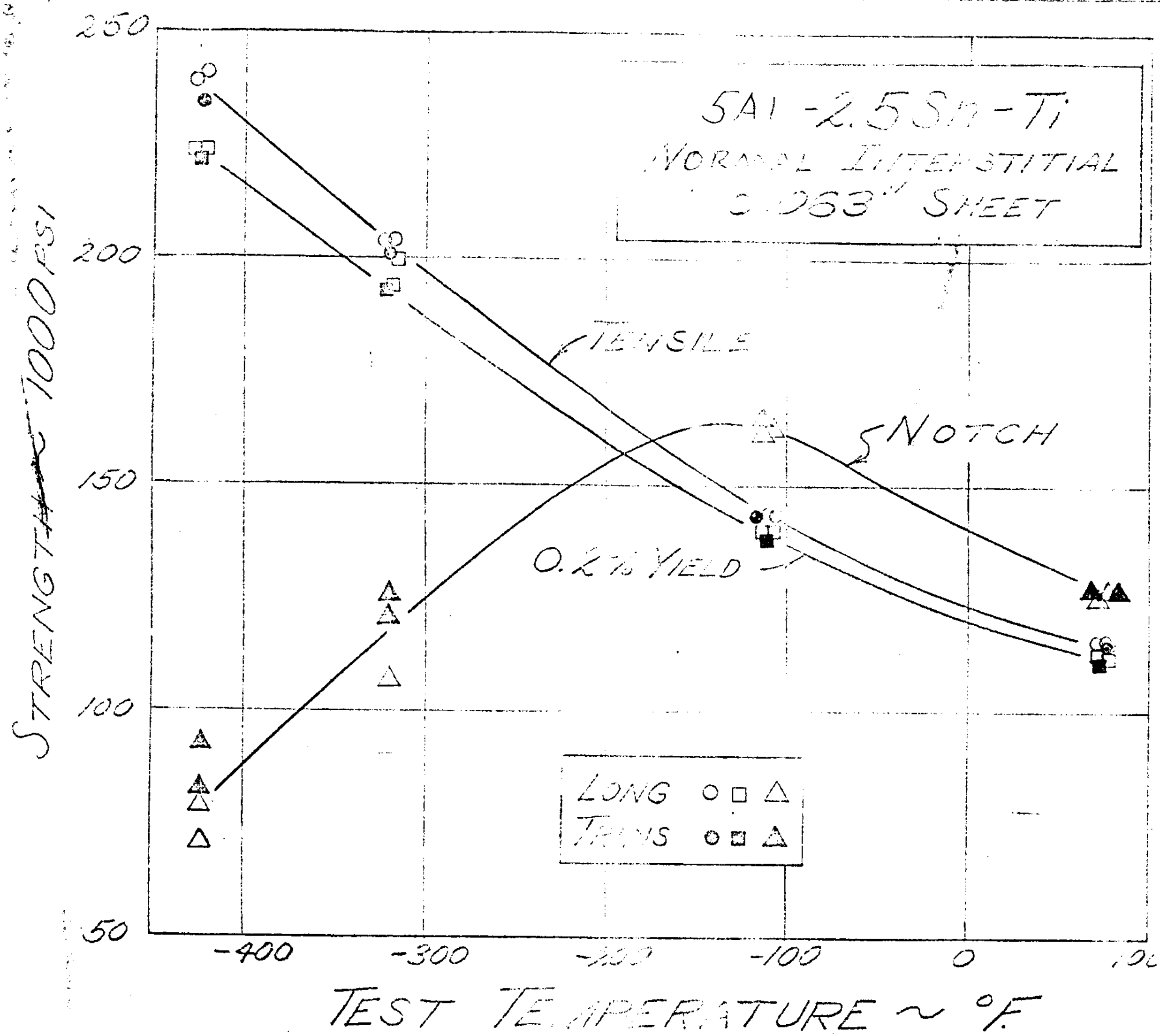


FIG. 3b: Influence of test temperature on smooth and sharp edge notch strength of normal interstitial 5Al-2.5Sn-Ti alloy sheet.

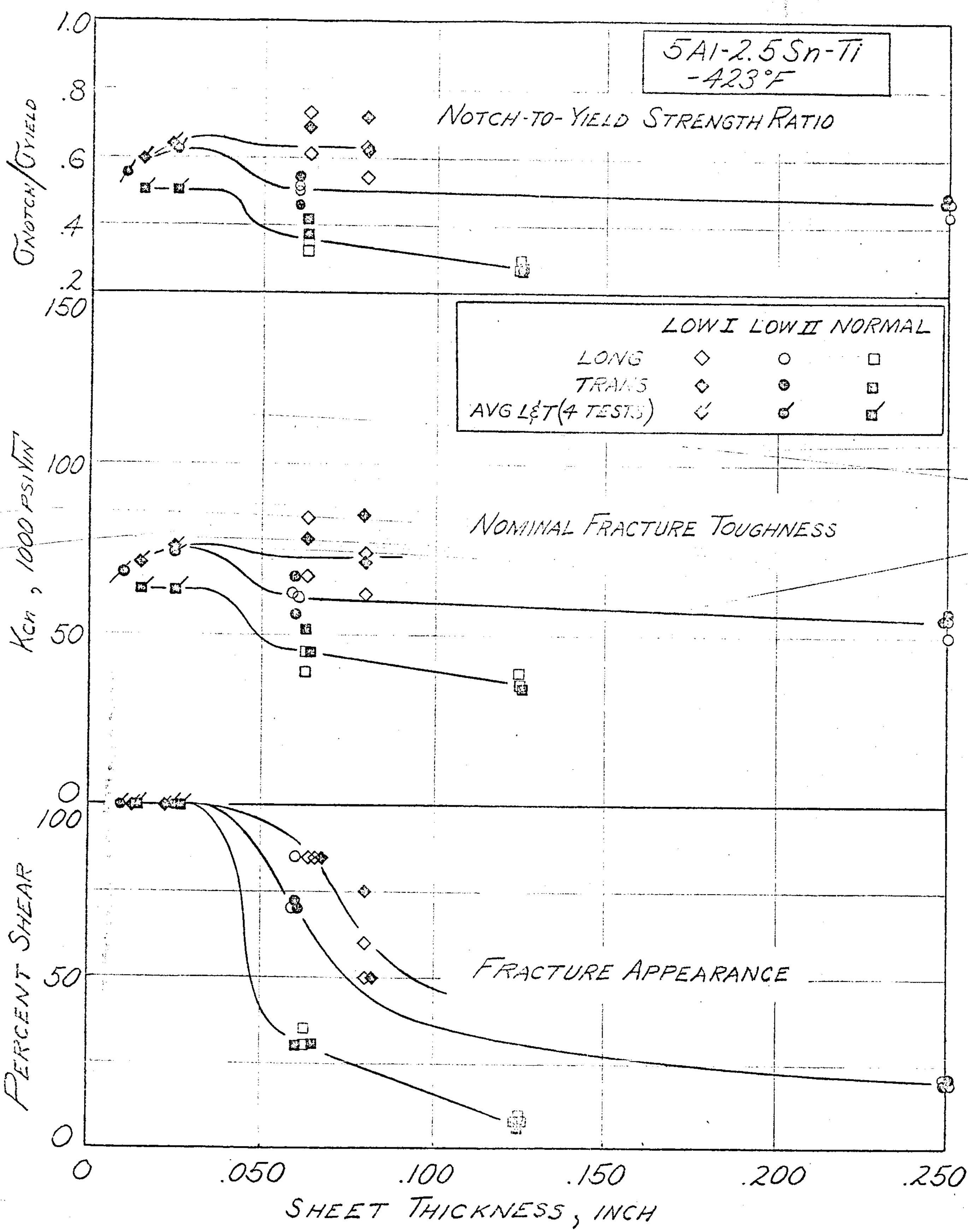


FIG. 4: Influence of sheet thickness on the -423°F sharp notch fracture characteristics of 5Al-2.5Sn-Ti alloy at three interstitial levels.

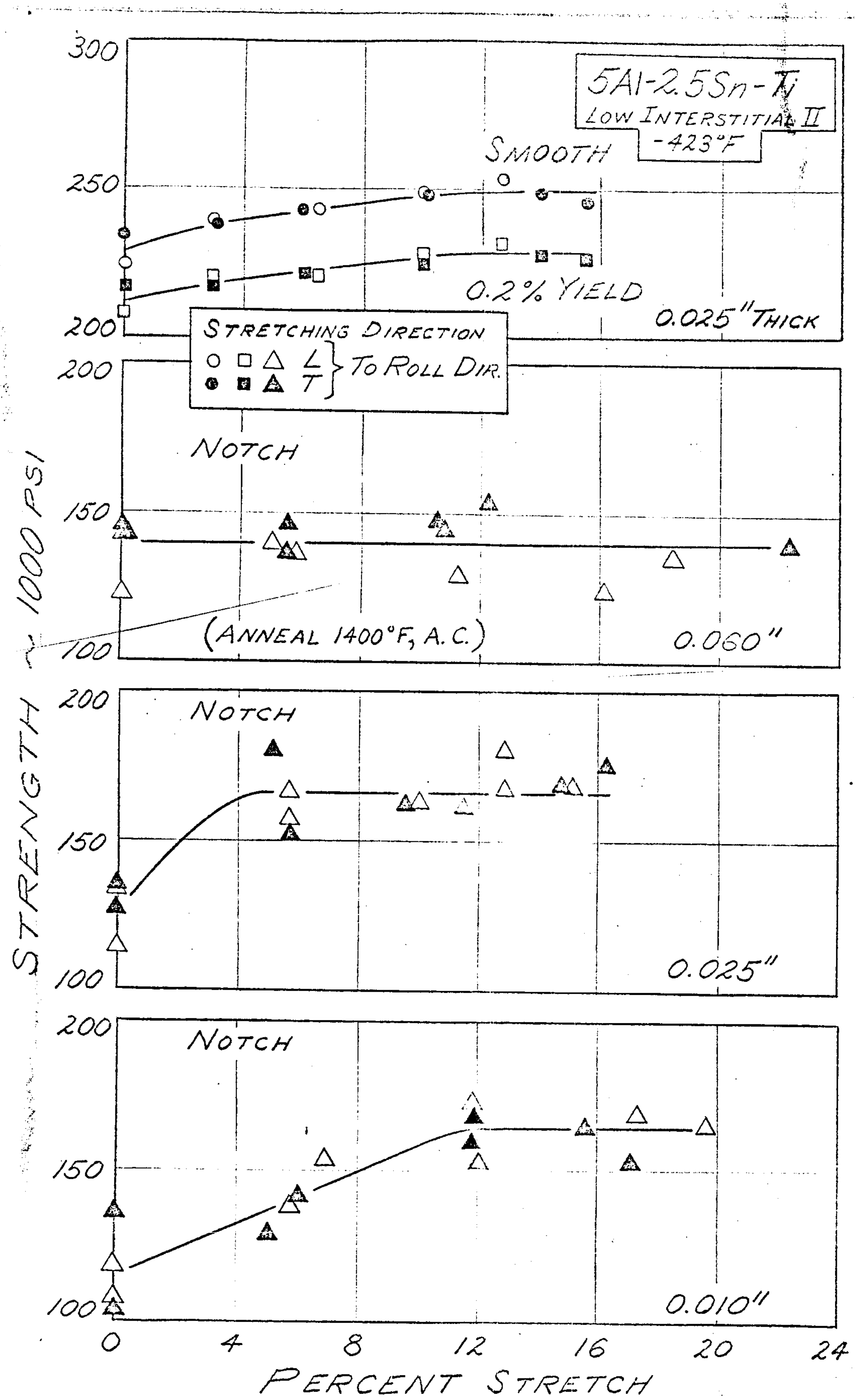


Fig. 5a: Influence of stretching on -423°F smooth and sharp notch strengths of low interstitial 5Al-2.5Sn-Ti sheet alloy. Testing direction coincides with stretching direction.

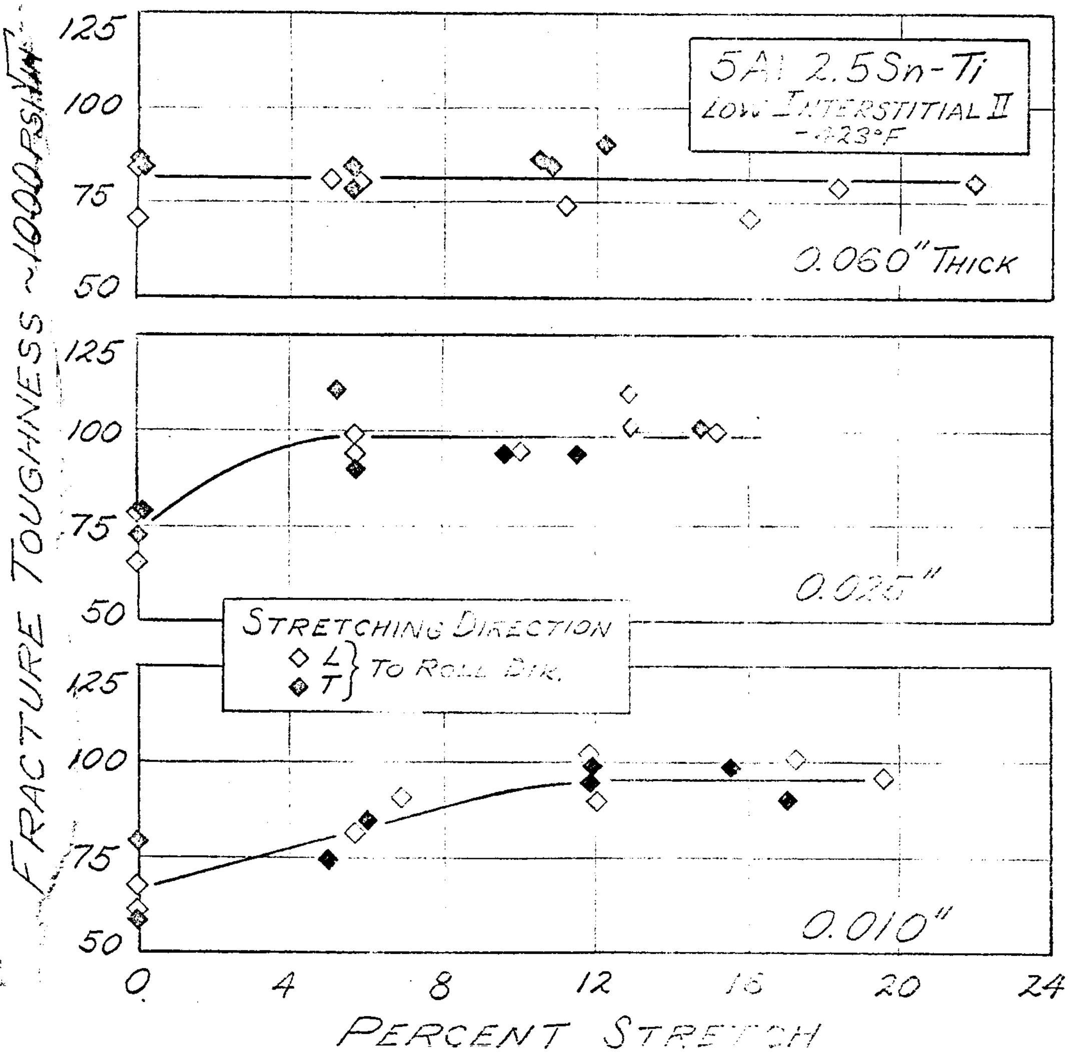


FIG. 5b: Influence of stretching on -423°F smooth and sharp notch strengths of low interstitial 5Al-2.5Sn-Ti sheet alloy. Testing direction coincides with stretching direction.

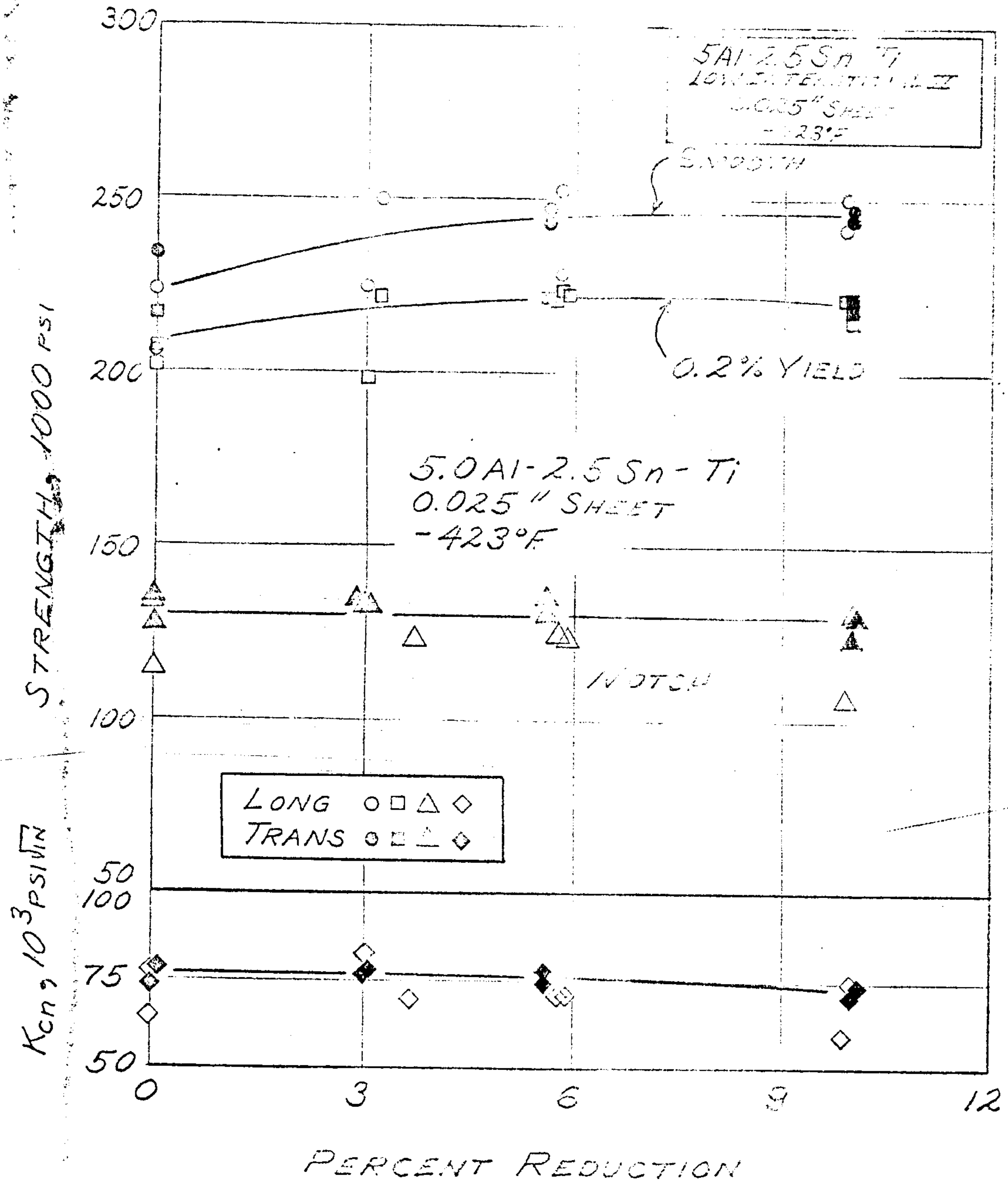


FIG. 6: Influence of cold rolling on -423°F smooth and sharp notch properties of low interstitial 5Al-2.5Sn-Ti sheet alloy.

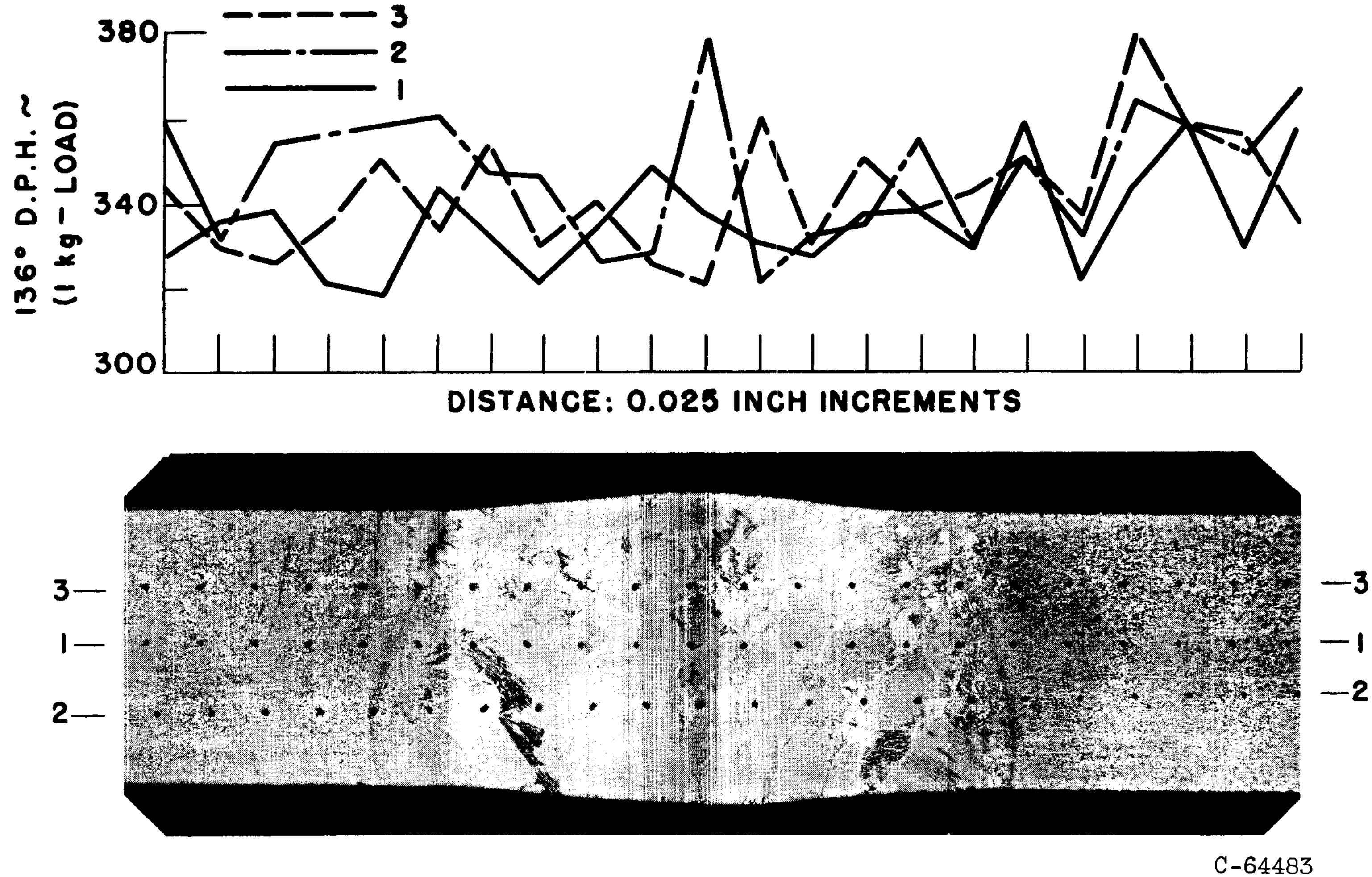


Figure 7. - Weld hardness survey for TIG welded normal interstitial 0.125 inch sheet. X12. Keller's etch.

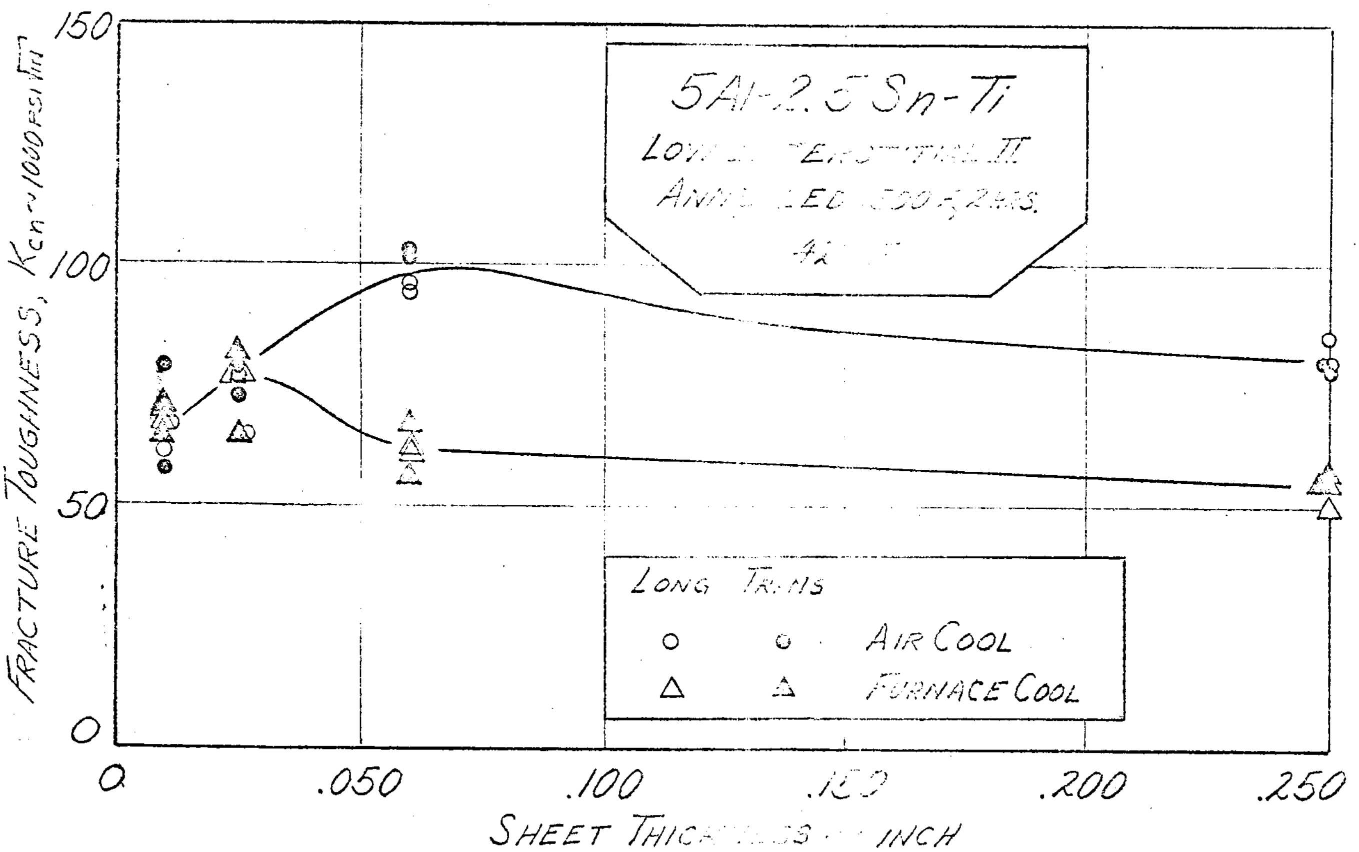
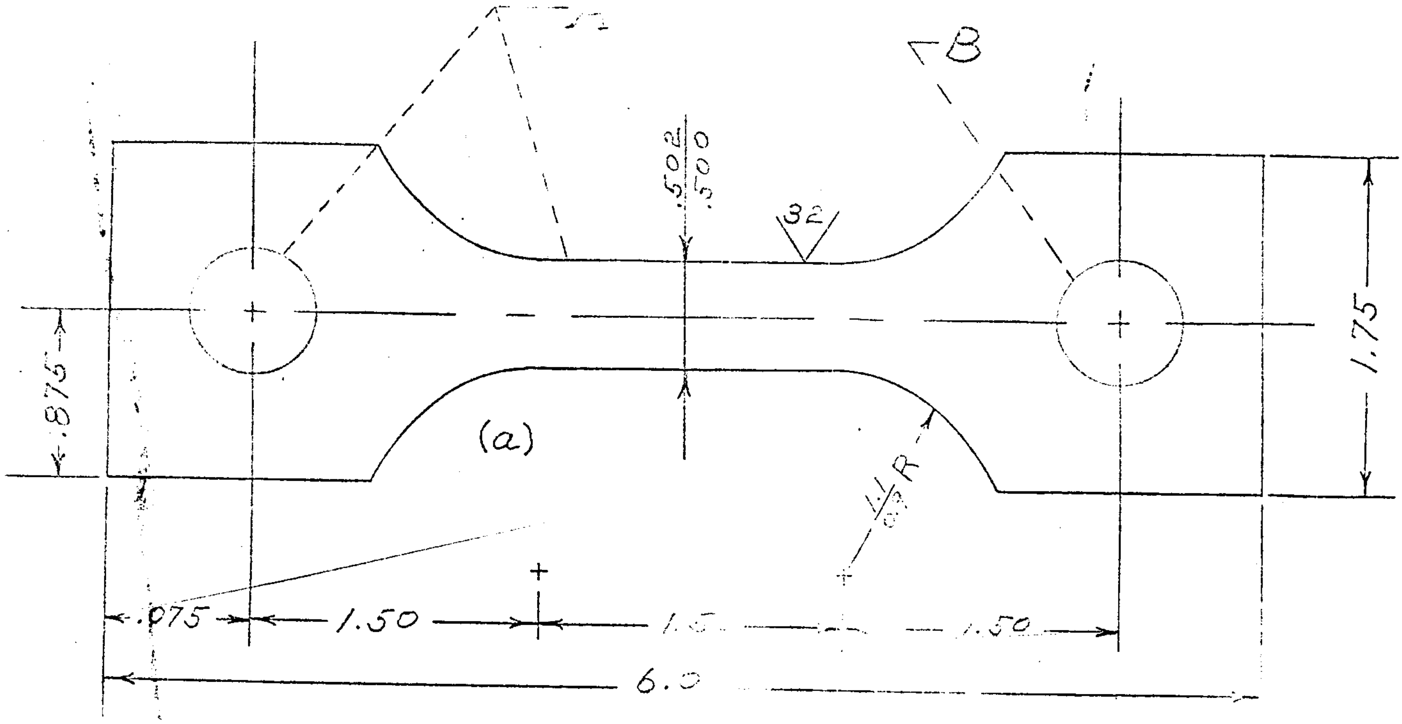
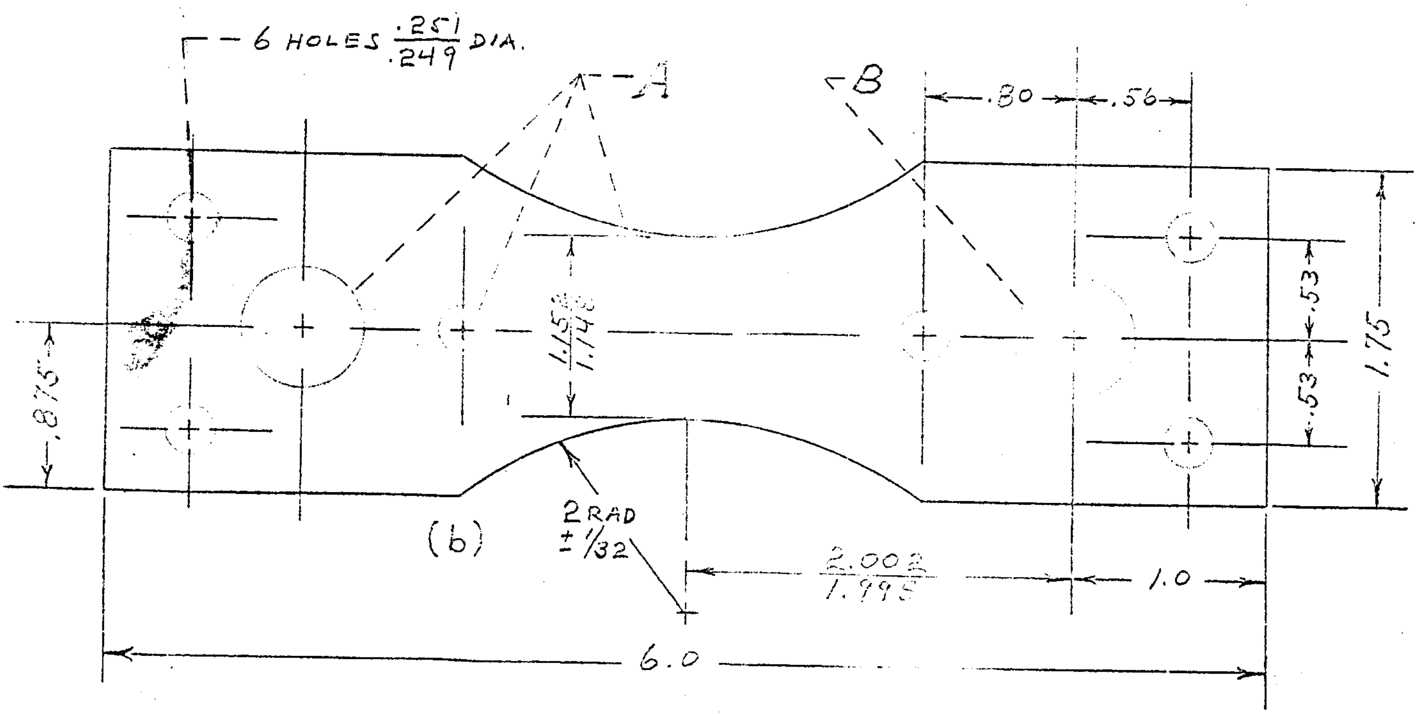


FIG. 8: Nominal fracture toughness as a function of sheet thickness for 5Al-2.5Sn-Ti low interstitial sheet air cooled and furnace cooled from annealing temperature.



Smooth



Notch

A SURFACES TRUE TO CENTERLINE WITHIN 0.001 IN.

B: 0.625 DIA. REF. 0.005 IN. MAX. CLEARANCE WITH LOADING PIN

ALL DIMENSIONS ARE IN INCHES

FIG. 9: Smooth and notch stretch specimen blanks.